MICRO-SEISMOMETERS VIA ADVANCED MESOSCALE FABRICATION

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ABSTRACT

The Department of Energy's National Nuclear Security Administration (DOE/NNSA) seeks revolutionary innovations with respect to miniature seismic sensors for the monitoring of nuclear detonations. Specifically, the performance specifications are to be consistent with those obtainable by only an elite few products available today, but with orders of magnitude reduction in size, weight, power, and cost. The proposed innovation calls upon several advanced fabrication methods and read-out technologies being pioneered by Silicon Audio, including the combination of silicon microfabrication, advanced meso-scale fabrication and assembly, and the use of advanced photonics-based displacement/motion-detection methods. Successful implementation will result in a commercial product roughly the size of a common USB flash drive with the ability to address advanced national security needs of the DOE/NNSA. Additional commercial market sectors include military/defense, scientific/instrumentation, oil and gas exploration, and inertial navigation.

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OBJECTIVES

The DOE/NNSA seeks revolutionary innovations with respect to miniature seismic sensors for the monitoring of nuclear detonations. The specific sensor specifications solicited are as follows:

- Size—less than 1 in^3
- Power—less than 100 mW
- Sensor self-noise—below United States Geological Survey Low Earth Noise Model, or approximately 0.5 ng/√Hz
- Dynamic range at least 120 dB over a frequency band of 0.2 to 40 Hz.

The proposed design innovation calls upon several advanced fabrication methods and read-out technologies being pioneered by Silicon Audio, including advanced mesoscale fabrication of mechanical proof-mass elements, photonics-based displacement/motion detection, microscale optoelectronic integration, and the integration of new types of closed-loop sensing modalities for high stability and high dynamic range. In what follows, we first summarize basic design considerations for any proposed technology aiming to meet the aforementioned specifications. We then briefly summarize some of our prior research with optical based motion detection and micromachined sensors.

Fundamental Design Considerations

A brief consideration of a few key design parameters for an accelerometer quickly reveals the challenges in achieving the noise specifications required by the DOE. For this purpose, a sufficiently accurate model for an accelerometer sensing structure is a simple spring-mass-damper system. Such a system is characterized by its mass, resonant frequency, and quality factor of resonance; M, f_o, and Q, respectively. Acceleration of this system results in an inertial force to the proof mass, which in turn results in a proof mass displacement proportional to the incoming acceleration. This displacement is measured in one of a number of ways (e.g., via capacitive, piezoresistive, or optical methods). There are two fundamental limits to the acceleration resolution of the sensor. The first is imposed by the resolution with which the proof mass displacements can be detected. This minimum detectable displacement (MDD) is expressed in m/√Hz and depends on the sophistication and design of the particular approach being used. The MDD is referred to input acceleration via the displacement sensitivity to acceleration of the system, which is expressed in $m/(m/s^2)$ and equal[1] to $1/(2\pi f_o)^2$. This relation allows the MDD to be referred to a minimum detectable acceleration (MDA) via

$$MDA_d = MDD * (2\pi f_o)^2 . \qquad (1)$$

For example, in order to achieve a MDA of 0.5 ng/√Hz with a system with 50 Hz resonance, the displacement of the proof mass must be resolved with amazingly high resolution—50 fm/√Hz.

The second fundamental limit to the acceleration resolution of the sensor is Brownian motion (i.e., thermal mechanical noise) of the proof mass. The acceleration referred thermal noise limit can also be expressed in terms of the fundamental system parameters via the well-known relation shown below (Gabrielson, 1993):

$$a_{tm} = \sqrt{\frac{8\pi k_b T f_0}{MQ}} \qquad (2)$$

where k_b is Boltzmann's constant and T is the ambient temperature. With this as background, design parameters meeting the challenging noise requirement can be identified. Table 1 summarizes three designs for discussion, all with a 50-Hz resonance.

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[1] This is obtained by recognizing that the inertial force is $F = M*a$, and the resulting displacement δ is equal to F/K where K is the system stiffness. The ratio M/K is simply $1/(2\pi f_o)^2$, which results in the cited expression.

Table 1. Summary of three mechanical designs

	fo (Hz)	M (kg)	Q	a_{tm} g/sqrt(Hz)
A	50	2.00E-06	100	1.63859E-08
B	50	2.00E-06	100,000	5.18166E-10
C	50	2.00E-03	100	5.18166E-10

Design A represents what has been demonstrated as the state-of-the-art in technologies based on micromachining (i.e., microelectromechanical [MEMS]). In fact, only a few research teams have rigorously demonstrated close to 20-ng/√Hz resolution from MEMS-based approaches. Most notably, T. Kenny and a research team at Stanford achieved 20-ng/√Hz resolution using electron-tunneling displacement sensing (capable of achieving 50 fm/√Hz) of a cantilevered proof mass combined with an electrostatic force rebalance architecture (Liu and Kenny, 2001).

The primary limitation in achieving a thermal noise level lower than 20ng/√Hz with any MEMS approach is the inherently small proof-mass. Doing so requires achieving very high resonance *Q*s (near 100,000 as summarized in Design B). This approach carries both vacuum packaging challenges and electronics design challenges, as all designs with a *Q* higher than unity must incorporate a closed-loop feedback system to realize the required flat frequency response (e.g., see Liu and Kenny, 2001; Standley and Pike, 2007). Primary challenges in achieving design type C include development of a robust, repeatable, and low-cost fabrication process for the larger mechanical proof mass elements and the integration of the proof mass structure with a high-fidelity motion detection technology. Silicon Audio is pioneering innovations to address both design types. In the remaining section, we present some preliminary work with micromachined sensors while highlighting one of several photonics based motion displacement technologies that can be integrated with theses sensors.

RESEARCH ACCOMPLISHED

The device structure in Figure 1 is an example of an innovative optical-based sensor and has been described in more detail in Hall et al., 2008). A detailed characterization of the displacement sensing technique when used in an advanced microphone structure shows 20 fm/√Hz displacement detection resolution—limited by quantum shot noise at the photodetectors (Hall et al., 2007).

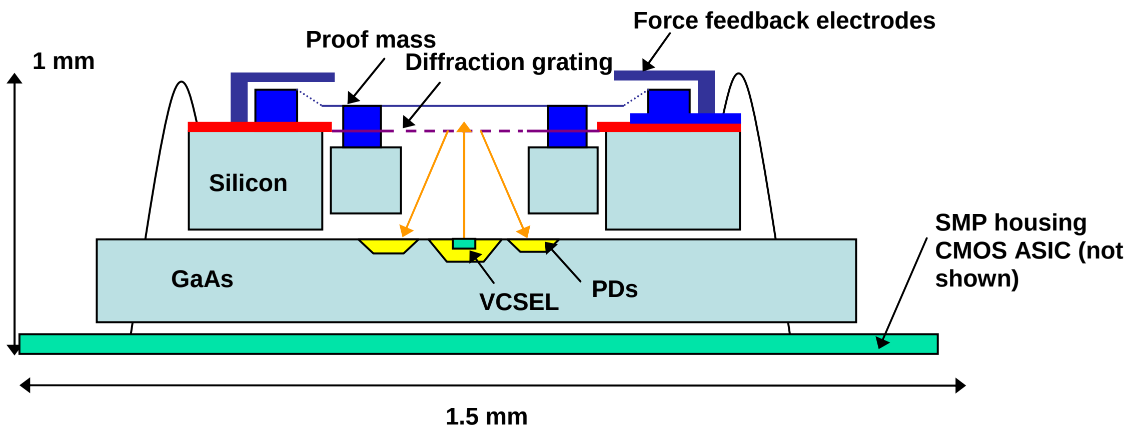

Figure 1. Schematic of the complete sensor innovation. Light from a semiconductor laser, such as a vertical cavity surface emitting laser (VCSEL), illuminates a diffraction grating fabricated on silicon. A portion of the incident light reflects directly off the grating fingers, while the remaining light travels between the grating fingers to the proof mass and back, to accrue additional phase. A diffracted field results, consisting of a zero order and higher orders, whose angles remain fixed but whose intensities are modulated by the relative distance between the proof mass and grating with the sensitivity of a Michelson-type interferometer. (This figure first appeared in Hall et al., 2008.)

Preliminary silicon micromachined proof mass structures are presented in Figure 2, and a measured dynamic impulse response of the proof mass displacement is presented in Figure 3, following application of a sharp electrostatic force pulse applied via the electrodes labeled in Figure 1. The Fourier transform of this measurement reveals a dynamic frequency response with a fundamental resonance of 220 Hz and *Q* equal to approximately 100 (for this test, the device was placed in a reduced atmosphere of 100 mtorr to emulate the type of conditions that can be achieved with wafer-level vacuum-packaging technologies). The structure has a 1.2-mg proof mass, from which one can infer a Brownian noise limit of 43.7 ng/√Hz for these proof-of-concept structures.

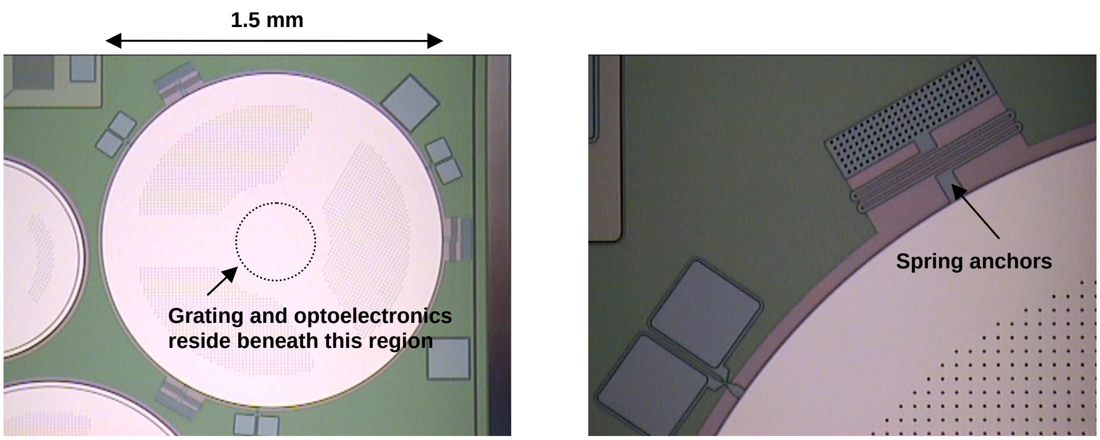

Figure 2. Micrographs of fabricated silicon structures shown schematically in Figure 1. (Left) Full view of 1.5-mm-diameter structure. (Right) Zoomed-in view highlighting a polysilicon spring that anchors the bulk silicon proof mass to the silicon substrate. (This figure first appeared in Hall et al., 2008.)

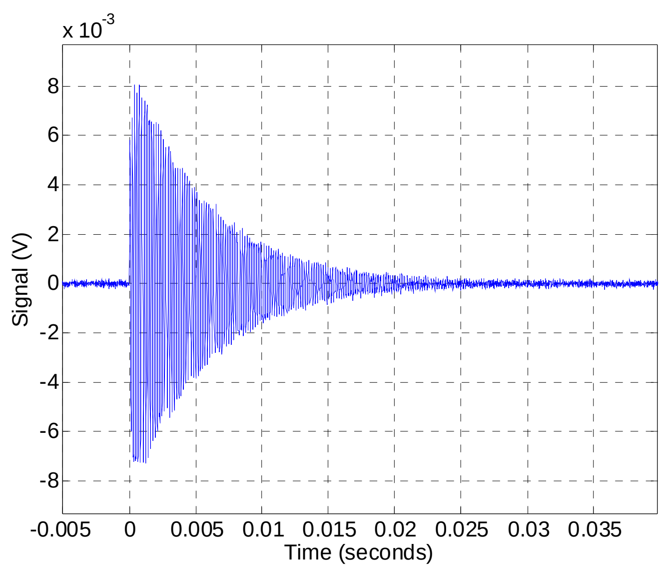

Figure 3. Measured impulse response of the structure presented in Figure 2. (This figure first appeared in Hall et al., 2008.)

CONCLUSIONS AND RECOMMENDATIONS

In what is to come, we will be focusing on the application of both silicon micromachining and optical-based motion-detection principles to create high-performance seismometers that can meet the NNSA's performance requirements. Future challenges for the MEMS-based designs summarized above are rooted in vacuum-level packaging to increase resonance *Q* and lower thermal-mechanical noise. Although not discussed here, Silicon Audio is also pioneering advanced mesoscale proof mass structures and integration procedures that overcome the small mass limitations of silicon micromachined structures while at the same time introducing new and unique integration challenges.

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